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14. ABSTRACT
This paper describes subscale, risk-reduction tests of an efficient method for applying a fuel film cooling (FFC) layer to the chamber wall of a liquid-hydrocarbon/gaseous-oxygen boost engine. The method reduces the amount of fuel required to meet wall temperature requirements relative to barrier film cooling approaches, thereby reducing the impact of FFC on specific impulse and contributing to a major AFRL IHPRPT goal for this propulsion category. The test specimens were designed and fabricated by Aerojet Corporation and make use of platelet technology to achieve a precise application of the film cooled layer. The test articles consist of two FFC panels, a calorimeter panel to establish baseline heat flux levels, and two injectors with differing levels of barrier film cooling. The principal measurement for characterizing the effectiveness of the panel designs will be the intact length of the FFC layer which will be measured using a combination of axially resolved heat flux measurements and post-test soot markings. Intact lengths will be measured for a range of fuel film injection flow rates and gas stream conditions. In this paper we report on a series of cold flow visualization tests utilizing stimulant fluids which were performed to provide additional insight into the behavior of the designs with respect to the levels of liquid stripping, entrainment and uniformity of the FFC layers.

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FILM COOLING OF LIQUID HYDROCARBON ENGINES FOR OPERATIONALLY-RESPONSIVE SPACE ACCESS

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ABSTRACT

This paper describes subscale, risk-reduction tests of an efficient method for applying a fuel film cooling (FFC) layer to the chamber wall of a liquid-hydrocarbon/gaseous-oxygen boost engine. The method reduces the amount of fuel required to meet wall temperature requirements relative to barrier film cooling approaches, thereby reducing the impact of FFC on specific impulse and contributing to a major AFRL IHPRPT goal for this propulsion category. The test specimens were designed and fabricated by Aerojet Corporation and make use of platelet technology to achieve a precise application of the film cooled layer. The test articles consist of two FFC panels, a calorimeter panel to establish baseline heat flux levels, and two injectors with differing levels of barrier film cooling. The principal measurement for characterizing the effectiveness of the panel designs will be the intact length of the FFC layer which will be measured using a combination of axially resolved heat flux measurements and post-test soot markings. Intact lengths will be measured for a range of fuel film injection flow rates and gas stream conditions. In this paper we report on a series of cold flow visualization tests utilizing stimulant fluids which were performed to provide additional insight into the behavior of the designs with respect to the levels of liquid stripping, entrainment and uniformity of the FFC layers.

INTRODUCTION

Fuel film cooling of combustion chambers will play a critical role in meeting IHPRPT goals for highly reusable hydrocarbon boost engines. The thermal stability limits of hydrocarbon fuels limit the maximum allowable wall temperature of the cooling channels and therefore the maximum allowable heat flux to the chamber wall[i]. Reductions in heat flux through fuel film cooling can also reduce the coolant flow and pressure requirements for the cooling channels. Fuel film cooling can increase chamber life by reducing the thermal stresses and the severity of the low-cycle fatigue environment for reusable engines. Efficient use of fuel films is critical because specific impulse is reduced when fuel rich mixtures adjacent to the wall exit the nozzle at non-optimal mixture ratio.

Several methods for applying fuel films have been devised[ii]. The simplest method is to incorporate a row of fuel orifices in the injector face adjacent to the chamber wall. This method tends to be inefficient because the film is largely dissipated by the throat of the engine which is the point of maximum heat flux. Transpiration of fuel through porous media could be a highly efficient method for applying fuel films; however, it is difficult to apply the film uniformly in the presence of strong pressure gradients inside the combustion chamber. It can also lead to an accelerating failure when a local hot spot results in blockage of the flow, starving the region of coolant and causing further increase and spread of high wall temperature. There have been several studies of slot injection of fuel. This method falls between the previous two in terms of the cooling efficiency but adds a significant technical challenge involving the incorporation of the slot injectors into a chamber wall that also contains regenerative cooling channels.

Optimizing a slot injection scheme to achieve the most efficient cooling requires a detailed knowledge of the near wall environment. When liquid fuel is introduced through a slot into a high velocity, reacting flow, a portion will be stripped from the surface and entrained into the gas stream. This portion may undergo secondary atomization before vaporizing and chemically reacting. The remainder will attach to the wall and form a film layer. The film will be subjected to

shear stress and convective and radiative heat flux from the overlying gas flow and as well as boundary conditions of no-slip, temperature and heat flux from the underlying wall. Surface disturbances may be created resulting in additional stripping and entrainment while heat transfer will vaporize the fuel. The addition of fuel vapor to the overlying boundary layer will reduce the energy of the gas and lower the rate of heat transfer to the film. Vaporization will also produce a “blowing” effect, or Stefan flow, due to the high rate of mass transfer that will further reduce the rate at which hot gas penetrates to the liquid film layer. After an initial heat up distance, the film will reach the so-called wet bulb temperature when the loss of energy by vaporization and conduction to the wall is balanced by the rate of heat addition. It is also possible that the fuel layer would transition to a supercritical state at which point surface tension would not exist and the rate of mixing with the overlying gas would increase. In either case, a fuel rich layer would persist for some distance downstream until mixing, decomposition, and oxidation eventually returned the gas temperature to the level that existed upstream of the slot. It may be efficacious to place a second slot and then a third and so on. The optimal design of a slot injection system may involve several injection points with slot widths, fuel mass flows and spacing that have been designed to meet specific wall temperature requirements while minimizing the negative impact on engine performance.

Demonstrations of the effectiveness and performance impacts of fuel film cooling are available. Volkmann reported heat flux results from a subscale (40K), calorimeter test article operating at 2000 psi on LOX/RP-1[iii]. RP-1 fuel films were introduced through an injection ring containing injection holes of 0.012” diameter and 0.033” spacing placed in a backwards facing step that protruded about 0.060” from the chamber wall. The ring could be located immediately downstream of the injector or at the start of the 2.53:1 contraction section. When the ring was located at the start of the contraction, a fuel film flow of 1.5 lbm/s (13% of total fuel flow in the subscale test article), reduced the heat flux at the throat from 66 Btu/in^2/s to 19 Btu/in^2/s. The impact on performance was 2% drop in c* efficiency. When the injection ring was placed next to the injector face, the same fuel film flow reduced the throat heat flux to 47 Btu/in^2/s, and the heat flux at the mid-point of the barrel section was reduced from 30 Btu/in^2/s to 10 Btu/in^2/s. Scaling these results to a full scale 500K engine, the film coolant required would be 1.6% of the total fuel flow and the impact on c* efficiency would be less than 0.25%. These results showed that the liquid fuel film coolant can be highly effective in reducing chamber wall heat flux with relatively low flow rates and without the complications and potential failure modes associated with transpiration cooling.

Kirchberger has published results from a bench-scale (1K) heat-sink test article operating at pressures up to 1500 psi on GOX and kerosene[iv]. Film coolants were introduced through an applicator ring that was located approximately half way between the injector and the contraction section. The ring allowed the coolant to enter the chamber through a continuous, circumferential slot. For comparable mass flow rates, kerosene was shown to be significantly more effective at reducing wall temperature than gaseous nitrogen.

AFRL, in collaboration with Aerojet Corp., has undertaken a program to evaluate the effectiveness of fuel film cooling for highly reusable, hydrocarbon boost applications. The goal of this project will be to develop a physics-based model for fuel film cooling that can be used to optimize slot injection schemes. This is a complex problem involving mass, momentum and energy transfer between gases and liquids in reacting, high temperature and high pressure flows. There are three specific objectives for this effort: (1) obtain data on the cooling effectiveness of RP-2, (2) determine the percentage of fuel required to maintain a specific wall temperature, and (3) evaluate candidate concepts that could be utilized in a highly reusable, hydrocarbon boost engine. In support of this effort, Aerojet has produced two film cooled test specimens, and an uncooled calorimeter specimen, that can be inserted into the AFRL EC-1 heat flux rig. In this report we describe the results of preliminary cold flow tests that were performed using inert, simulant fluids at near-atmospheric conditions.

RESULTS AND DISCUSSION

This The primary objective of the cold flow testing was to verify that the flow issuing from the slots was uniformly distributed across the slot and remained attached to the specimen's surface. A transparent, acrylic mockup of the EC-1 heat flux rig was fabricated for the cold flow testing. The hot gas flow was simulated with gaseous nitrogen and the RP-2 was simulated with water. A test matrix was developed based on matching liquid flow rates and momentum flux ratios for gas and liquid streams with the hot fire conditions. Three values for liquid flow and three values for gas flow were selected. The momentum flux values for the liquid stream were based on a velocity calculated assuming the liquid flow filled the exit area of the slots.

Mom. Flux Liquid	Mom. Flux Gas	Momentum Flux	Mass Flow Rate Liquid	Mass Flow Rate Gas
Pa	Pa	Ratio	kg/s	kg/s
200	33000	165	0.00610	0.157
200	66000	330	0.00610	0.256
200	99000	495	0.00610	0.355
400	33000	83	0.00862	0.157
400	66000	165	0.00862	0.256
400	99000	248	0.00862	0.355
600	33000	55	0.01056	0.157
600	66000	110	0.01056	0.256
600	99000	165	0.01056	0.355

Table 1 Test conditions

Gas flow was metered with a sonic nozzle. After the nozzle expansion, the gas was passed through a heat exchanger to bring the static temperature up to near ambient in order to prevent icing in the test section. The liquid flow was metered with a cavitating venturi. The target momentum flux values at near ambient conditions required gas flow with Mach numbers up to 0.6. Stagnation and static pressure probes were installed in the test article to obtain Mach number measurements.

A Vision Research Phantom v7.3 camera operating at 6688 frames per second was used to record video of the flow. Illumination was provided by a 200 Watt quartz halogen lamp. The test article was oriented vertically with the flow of gas downwards.

For all test conditions the liquid flow issuing from the slots was uniformly distributed across the channel and liquid was observed to flow along the surface of the specimens. The liquid issuing from the slot did not fill the slot. The liquid issued as thin film along the trailing edge of the slot. Since the liquid did not fill the slot as assumed, the calculations for momentum flux of the liquid are not valid. The actual momentum flux of the liquid issuing from the slot will depend on the film thickness which may vary depending on the test conditions. Therefore in the following, the data is presented as a function of the mass flow of liquid

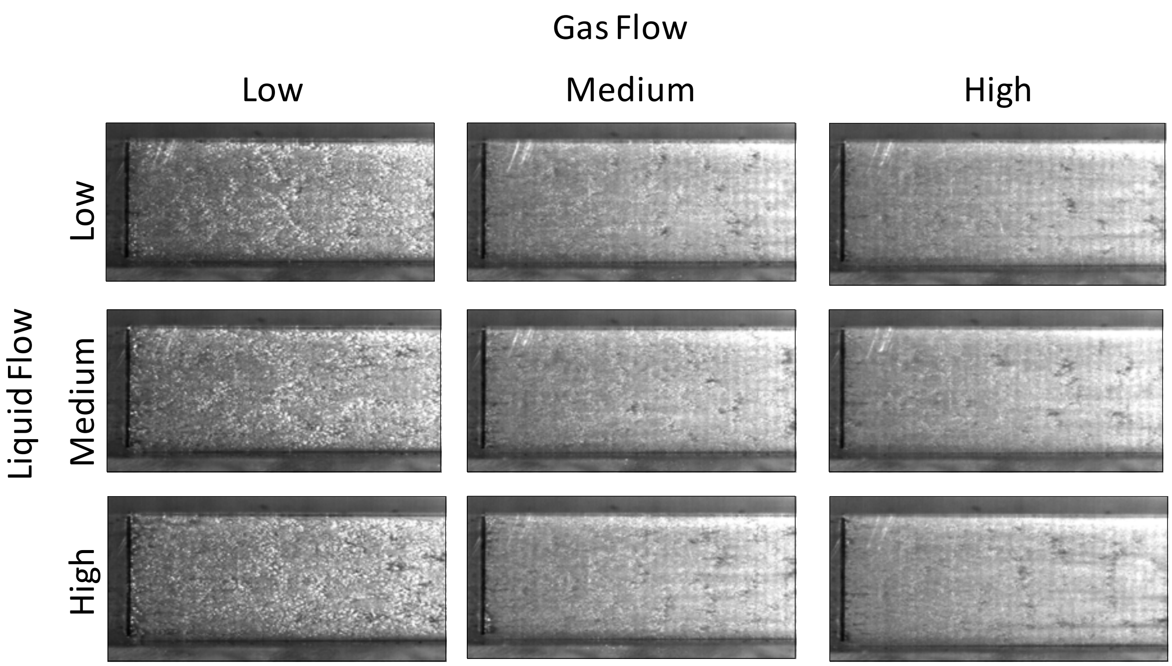

Fig. 1 Images of film flow for conditions shown in Table 1

For low gas flows, surface tension acted to draw the flow into the center of the channel and liquid void areas opened up along the sides of the channel. While this behavior could be problematic for cooling the square section examined here, it is unlikely to occur in typical rocket operations where the film would be annular. As the gas flow rate was increased, the increased shear resolved this issue and the film covered the surface of the coupon. The videos also showed streaks that were attributed to liquid that was entrained into the gas flow at the point of injection. These streaks were not in the same plane as the film surface.

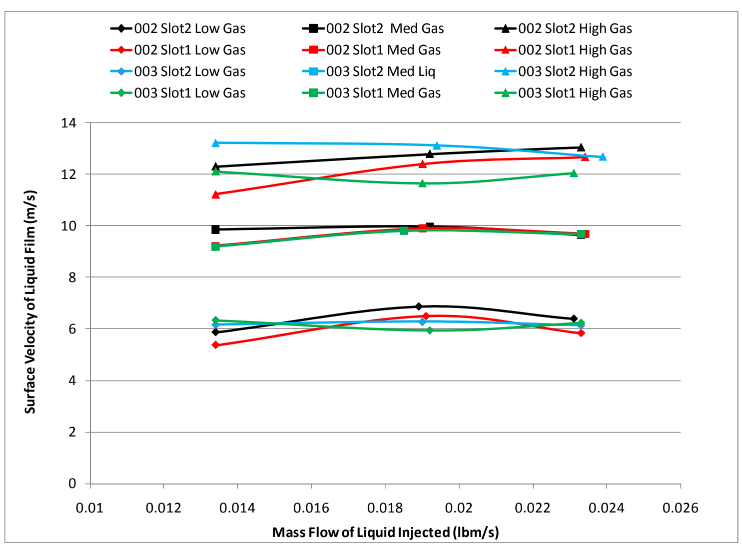

Fig. 2 Surface velocity of liquid film

The liquid surfaces exhibited small scale features that could be tracked from frame to frame allowing measurement of the surface velocities. Fig. 2 contains the data. Each point is an

average of 10 measurements. The surface velocities are independent of the amount of liquid injected and a strong function of the gas flow rate. There does not appear to be any consistent trends between the two test specimens or the two slots on each specimen.

The total amount of injected liquid that transitions into the film and its thickness are important characteristics of a film cooling layer. Direct measurements of these quantities are technically challenging. Estimates can be obtained using a momentum balance. At the surface of the liquid film the shear stress in the gas, τ_g, must equal the shear stress in the film.

$$\tau_g = \mu \frac{V_{surface}}{\delta} \tag{1}$$

The shear stress in the gas can be estimated using standard methods for predicting pressure loss in internal flow[5]. The roughness of the surface increases the shear stress above the value for a smooth wall. A correlation for friction factor was used to estimate the effect[v].

$$f = f_{smooth}\left[1 + 24\left(\frac{\rho_L}{\rho_g}\right)^{1/3}\frac{\delta}{D}\right] \tag{2}$$

The calculated film thicknesses, δ , are given in figure 3. The film thickness is seen to be independent of the initial rate of injection.

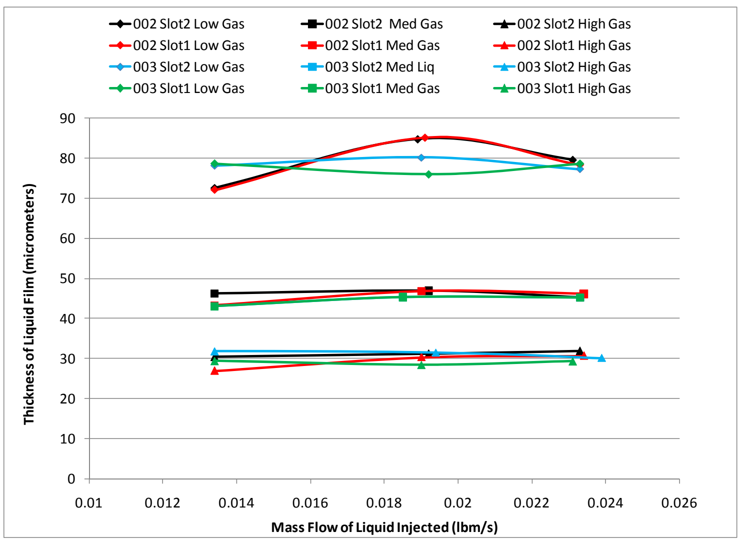

Fig. 3 Liquid film thickness

The film thickness can also be expressed in wall coordinates[vi].

$$\delta^+ = \frac{\delta}{v}\sqrt{\frac{\tau_g}{\rho}} \tag{3}$$

The δ^+ values are clustered around a value of 20. The thickness is independent of the initial mass injected and is the same for both specimens and slot positions. This suggests that there is a stable equilibrium value for δ^+ of the liquid layer.

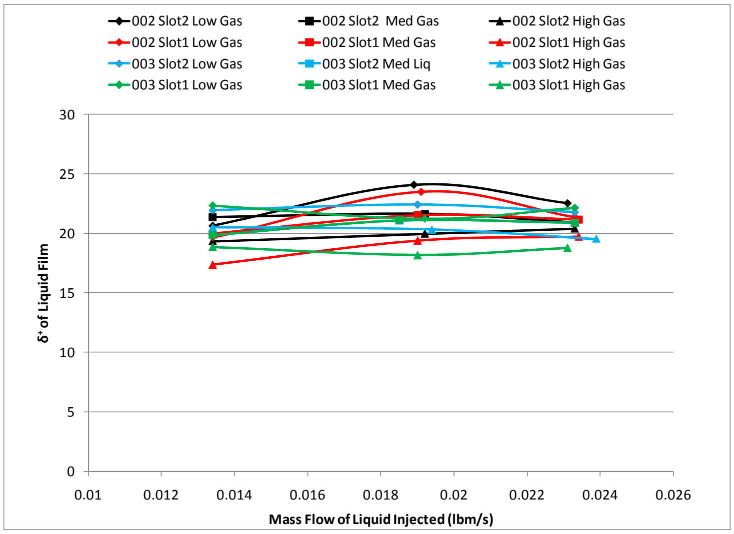

Fig. 4 Liquid film thickness in wall coordinates

With the surface velocity and thickness determined, the mass flow rate of the attached film was calculated. The data for both specimens and slot locations was averaged. Figure 5 shows the mass flow rate remaining in the liquid layer as a function of the initial mass flow rate injected. If all the liquid that was injected attached to the wall, the data would fall on the diagonal dashed line. The distance below the line represents amount of liquid that was entrained into the gas phase. The amount of liquid lost to entrainment increases with the velocity of the gas flow. At low gas flow and low liquid flow nearly all the injected liquid remains in the wall layer. For the high gas and liquid flows, over half is entrained. For a fixed level of gas flow, the liquid contained in the layer is nearly independent of the amount that was injected. This implies that the gas flow determines the maximum stable amount that can remain attached to the wall. Any amount above this is unstable and becomes entrained.

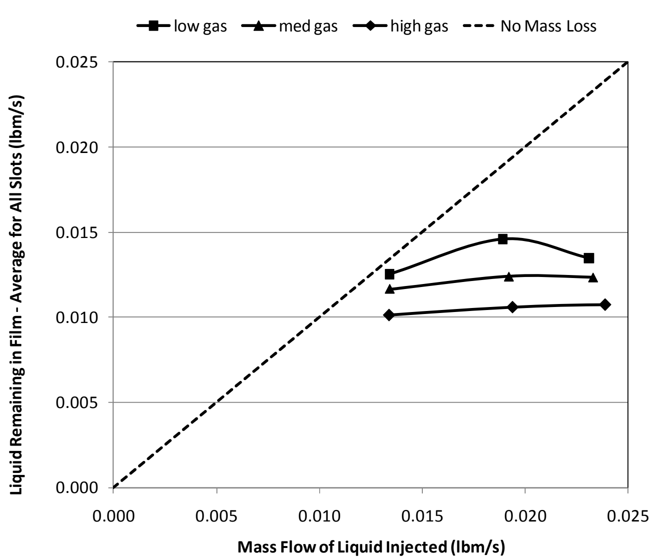

Fig. 5 Mass flow of liquid contained in wall film.

These results combined with the previous results on the δ^+ value for the liquid layer suggest the following explanation. The liquid issues from the slot and a fraction is immediately entrained into the gas flow. The balance remains attached to the wall. The thickness of the layer adjusts to the local conditions. The thickness of the film and its surface velocity adjust to match the local shear stress at a δ^+ value of 20. This is the maximum thickness that can remain attached to the wall in these shear driven flows before the surface disturbances become large enough for stripping to occur. This sets the initial thickness and mass flow rate contained in the film cooled layer. There is no minimum thickness for the film. Vaporization will act to reduce the thickness and mass flow rate of the film in both dimensional and wall coordinates until it is entirely consumed. As the film is vaporized it will become increasingly stable to flow disturbances.

SUMMARY AND CONCLUSIONS

Cold flow tests were performed to evaluate the performance of a slot injection scheme for liquid fuel film cooling of rocket combustion chambers. The initial mass flow rate contained in the film layer as well as its thickness was shown to be a function of the gas flow rate only and independent of the mass flow rate of injected liquid. Based on measured values of the surface velocity of the liquid film and some basic assumptions regarding the scaling of the layer in wall coordinates, it was found that the liquid layer was stable at a non-dimensional thickness of 20. Establishing these initial conditions for the liquid film may aid in the design of injection systems including the specification of the slot spacing and mass flow.

FUTURE WORK

This work can be extended in several ways. The initial thickness of the film issuing from the slot should be measured and this length scale should be used to form a Weber number. The amount of liquid initially entrained into the gas flow should be a function of this Weber number. The study should be repeated with RP-2 or a simulant fluid that has the same surface tension and viscosity.

The mass flow rates of liquid should be reduced at each value of gas flow to determine if all of the liquid transitions into the film layer at low injection rates. The y^+ values for the low flow conditions should be measured to determine if the value of 20 is universal or only occurs when the liquid layer flow rate is controlled by the initial entrainment at the point of injection.

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